How do we detect photons?

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Self-introduction

- Researcher of high energy physics (experiment)
- In the past,
  - Neutrino and nucleus
  - Polarized protons
  - Heavy ions

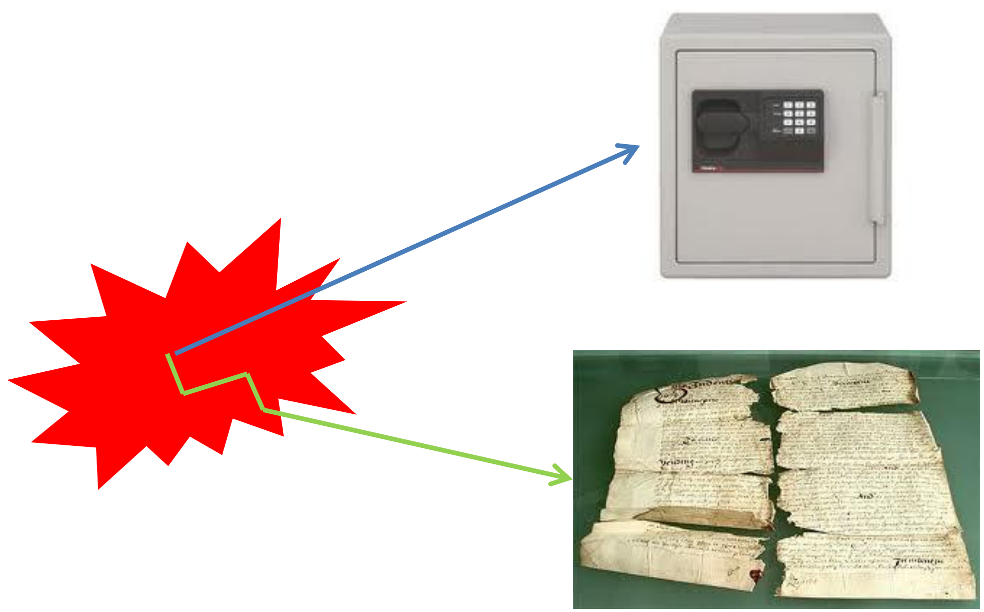
In short

Hit them, collect debris, imagine what happened.
A lot of events.

*) Difference: $E=mc^2$

Photon in high energy physics

- The photon is an important probe.
- Since the photon doesn't feel the strong force, it brings information undisturbed from the collision.



Photon

Other particles

Goal for today

- What is photon?
- Photon interactions
- What is Electromagnetic Calorimeter?
- Application example (PHENIX experiment)

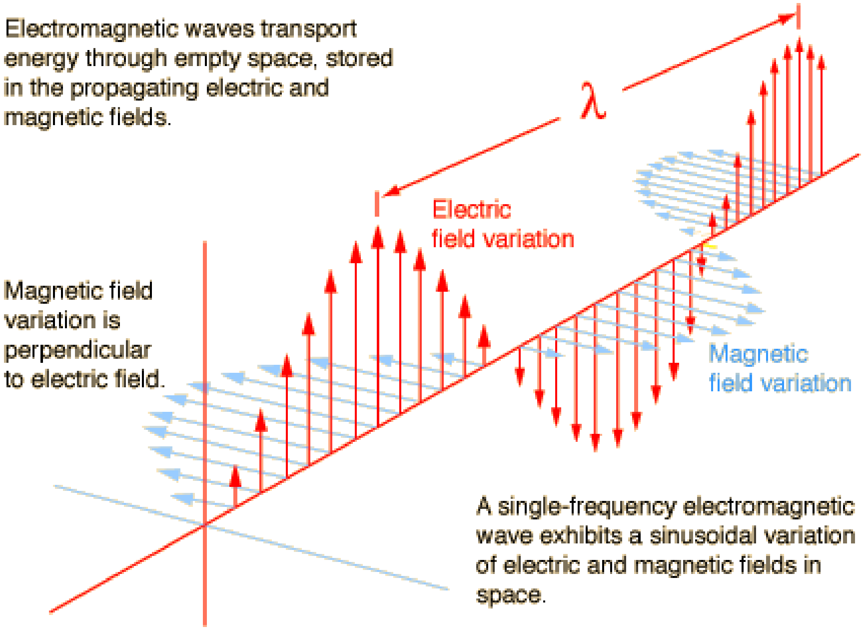
Feel free to ask any question.

Photon (= EM wave)

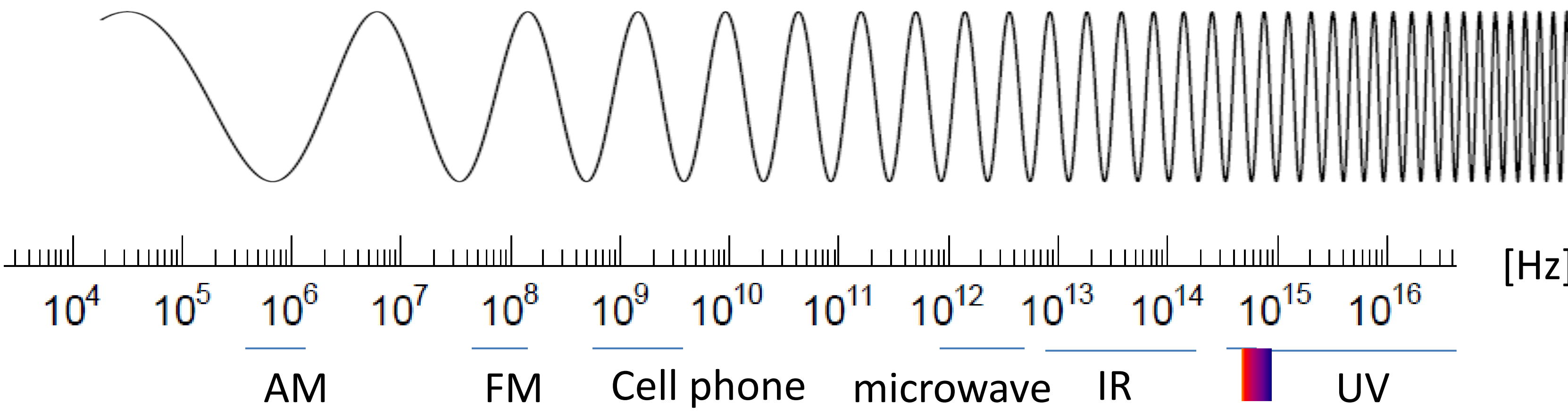
A high frequency end of the electromagnetic wave.

$$
\begin{aligned}
rot\mathbf{E}(\mathbf{x},t) + \frac{\partial \mathbf{B}(\mathbf{x},t)}{\partial t} &= 0,\\
rot\mathbf{H}(\mathbf{x},t) - \frac{\partial \mathbf{D}(\mathbf{x},t)}{\partial t} &= 0,\\
div\mathbf{D}(\mathbf{x},t) &= 0,\\
div\mathbf{B}(\mathbf{x},t) &= 0.
\end{aligned}
$$

$$
\begin{aligned}
rot(\Delta - \epsilon\mu\frac{\partial^2}{\partial t^2})\mathbf{E}(\mathbf{x},t) &= 0,\\
rot(\Delta - \epsilon\mu\frac{\partial^2}{\partial t^2})\mathbf{B}(\mathbf{x},t) &= 0
\end{aligned}
$$



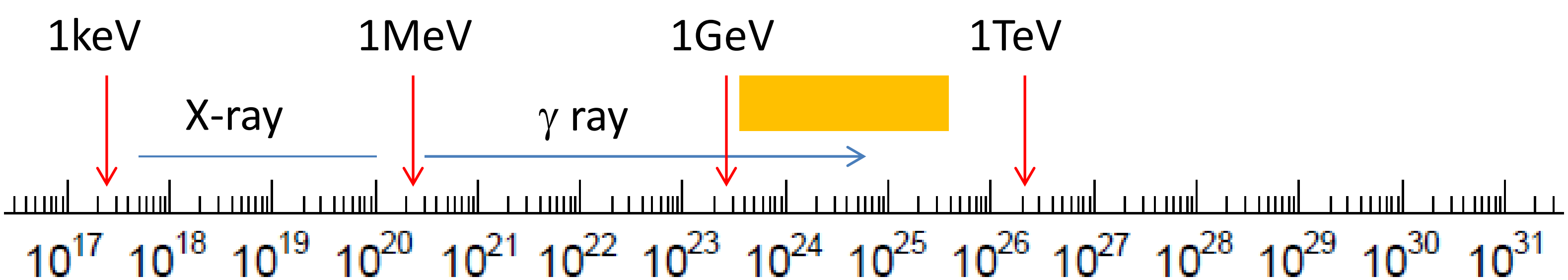
Photon (=EM wave)



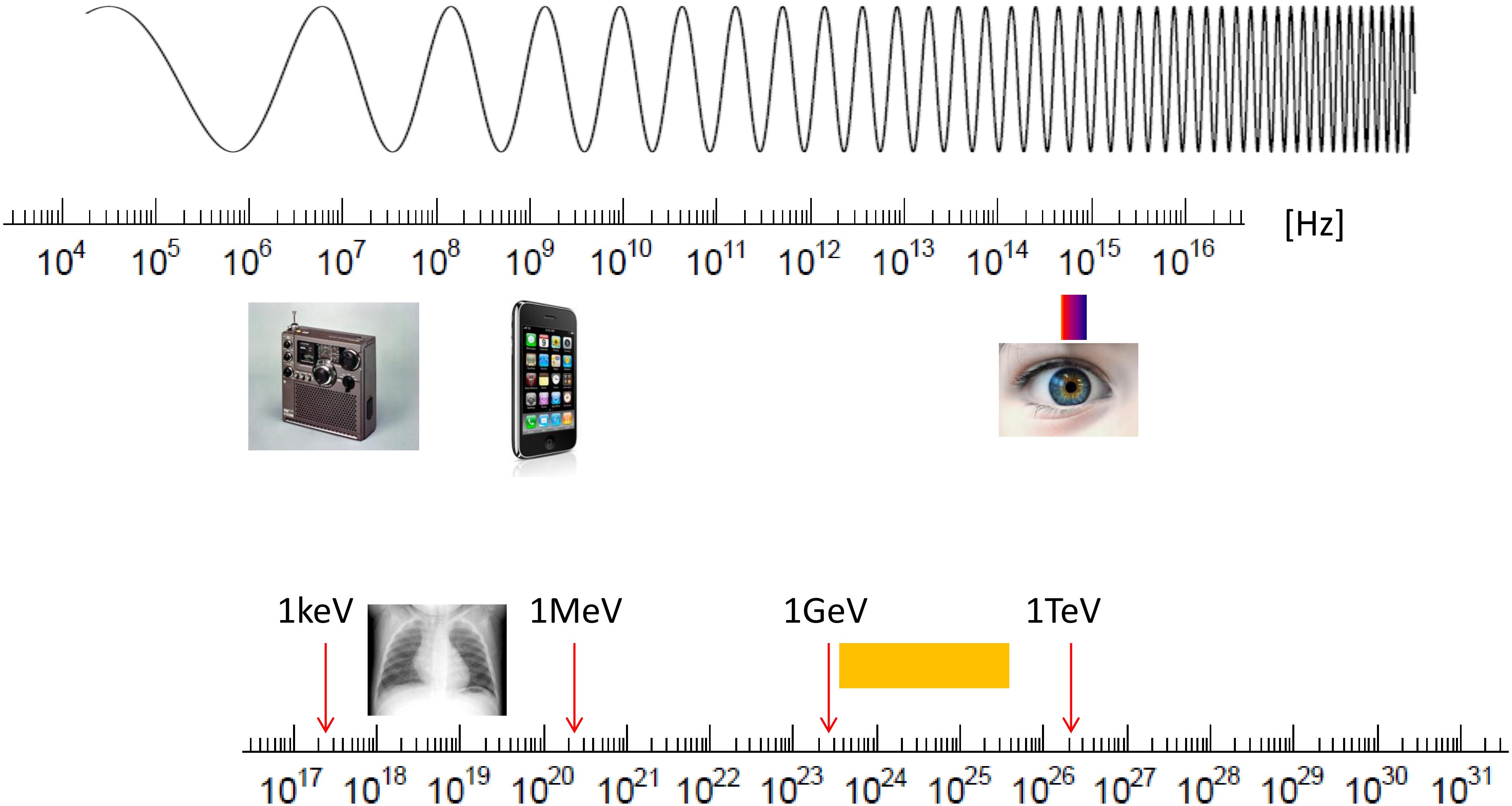
$E=h\nu$

$h=6.6*10^{-34}$ [Js]

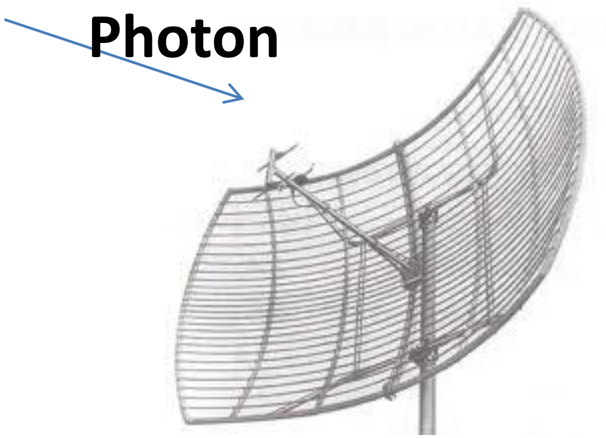
$1eV=1.6*10^{-19}$[J]



Photon detector examples



Detection principle



Sensor

Amplifier

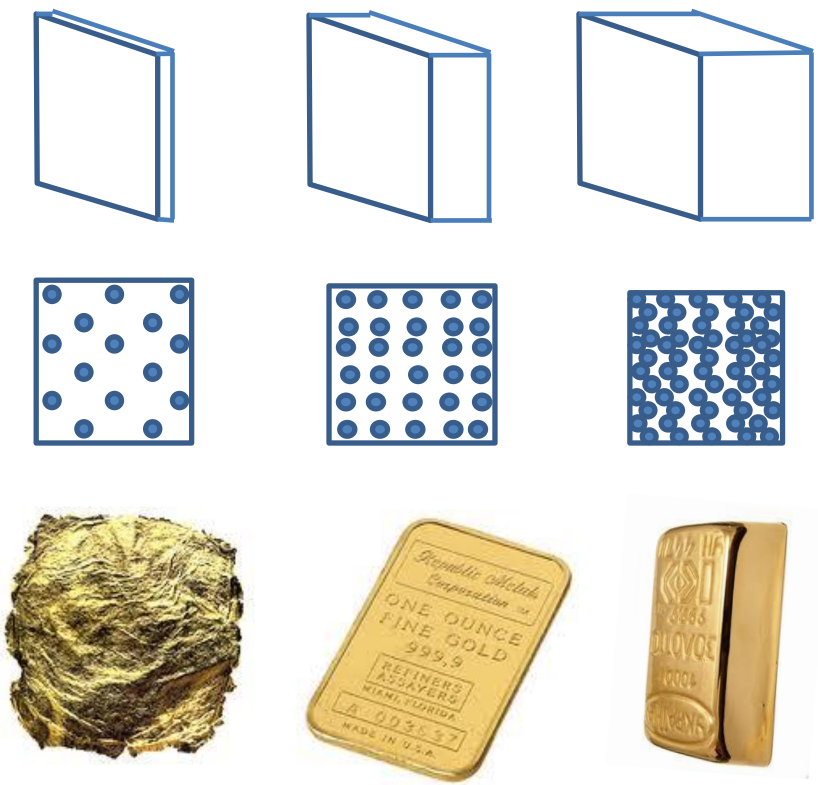
Measure

*) It is not specific to the photon detection.

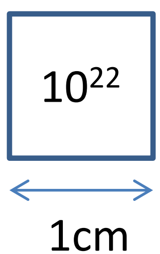
Strength of interactions

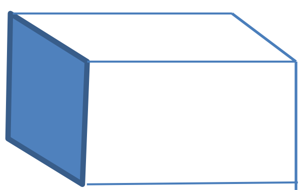
- Image: wave $\rightarrow$ particle
- Cross section (barn)

$$1 \text{ barn} = 10^{-28}\ m^2 = 10^{-24}\ cm^2$$



Ex) Lead 100barn = 10^{-22} cm^2

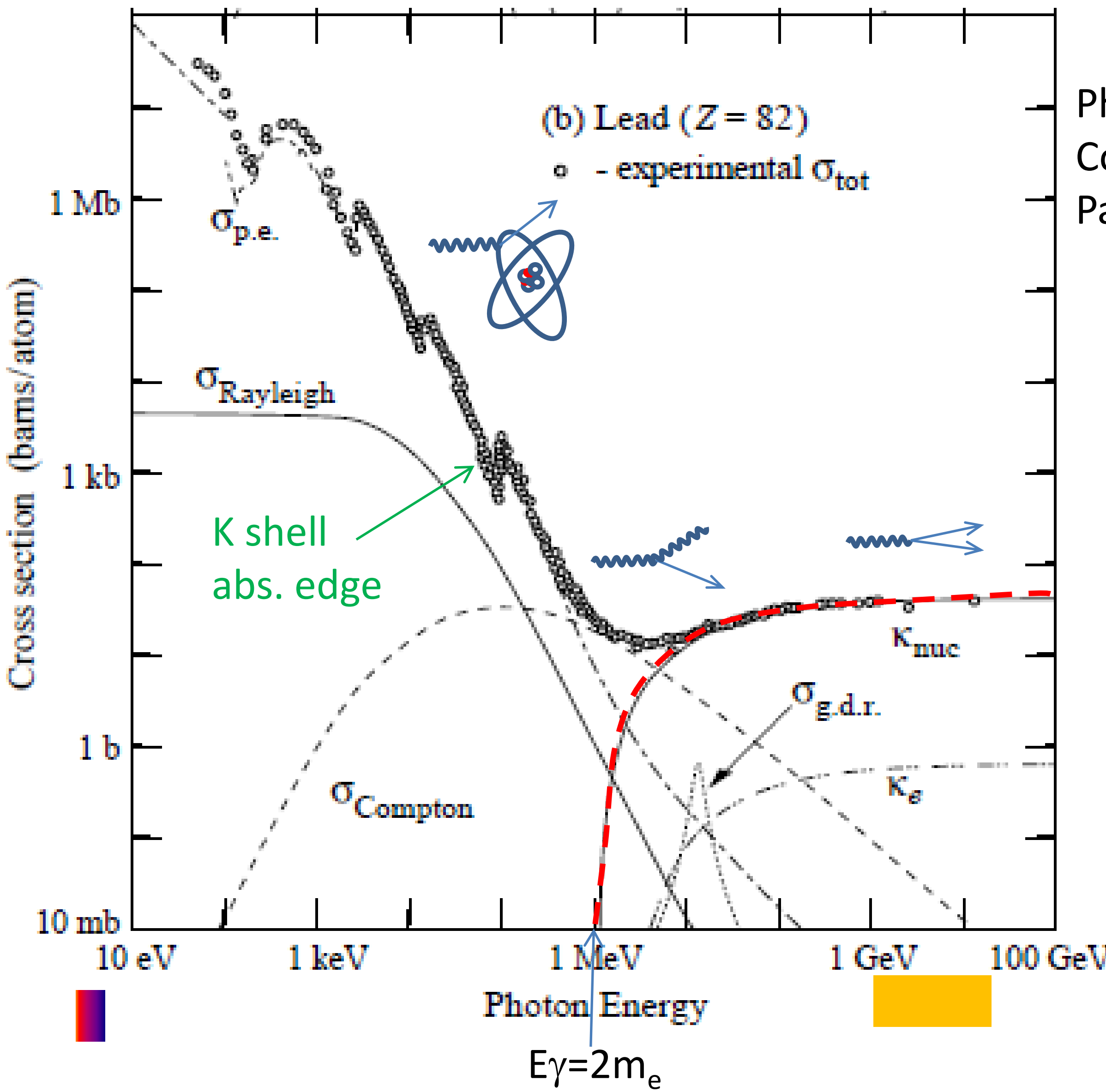




$10\text{^}22/N_A * A/\rho = 3$ [cm]

$\rho = 11.35\ g/cm^3$
$A = 207.2$
$N_A = 6.02 * 10^{23}$

Cross section of Lead



Photoelectric effect
Compton scattering
Pair creation, photon conversion

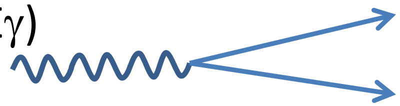
When $E\gamma > 2m_e$
Electrons become friend.

Photon conversion

It happens only in the material.

(E, **p**)

($E\gamma$,0,0,$E\gamma$)



e+ ($\sqrt{(m_e^2+p_x^2+p_z^2)}$, p_x,0,p_z)

e- ($\sqrt{(m_e^2+p_x^2+p_z^2)}$, p_x,0,p_z)

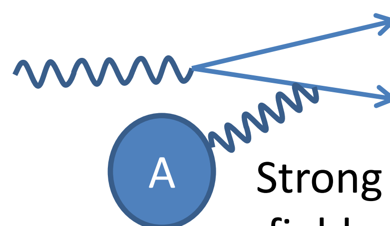
Conservations

Momentum $$E_\gamma = 2p_z$$

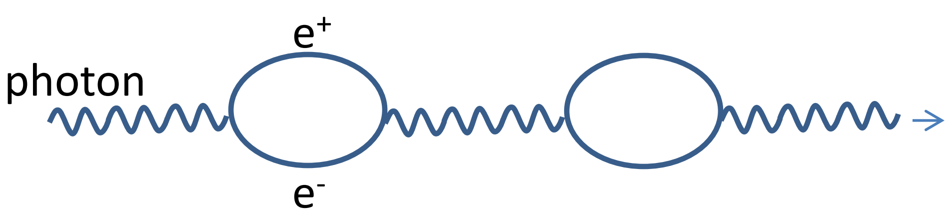
Energy $$E_\gamma = 2\sqrt{m_e^2 + p_x^2 + p_z^2}$$

Even p_x=0, they can not consist together.

It needs a help from the nucleus.

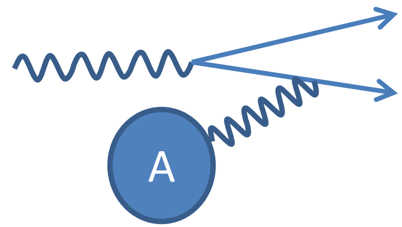


Strong electromagnetic field near the nucleus.

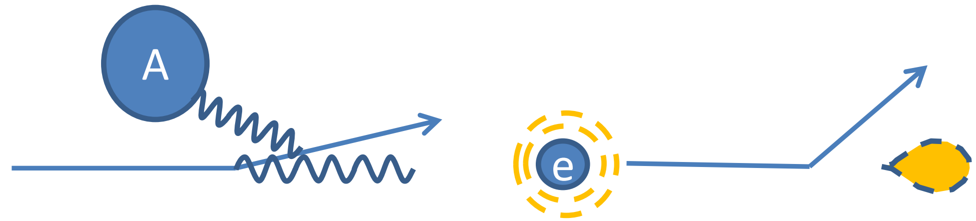


Electromagnetic shower

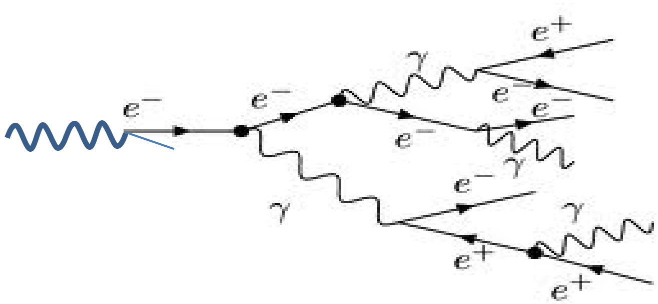
Photon converts to electrons



Electrons also emit a photon (Bremsstrahlung)



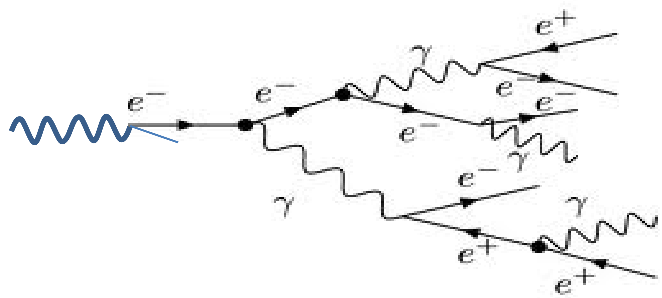
Electromagnetic cascade shower



(This particular picture is an image.)

Electromagnetic shower

Electromagnetic cascade shower



Typical length for one generation (= radiation length, X_0) X_0~$180A/Z^2$ [g/cm^2]

- Development of cascade shower
  - $N(t) = 2^{t}$
  - $E(t)$/particle = $E_0 \times 2^{-t}$

t in radiation length

- Process continues until $E(t) < E_c$
  - $T_{max} = \ln(E_0/E_c)/\ln 2$

$$N_{total} = \sum_{t=0}^{t_{\max}} 2^t = 2^{t_{\max}+1} - 1 \approx 2 \cdot 2^{t_{\max}} = 2\frac{E_0}{E_c}$$

Ec: critical energy
radiation loss = ionization loss
depends on the material.
Ec~550MeV / Z

- Moliere radius $R_M = \frac{21MeV}{E_c} X_0 \, [g/cm^2]$

90% included

What happens at end of day?

Radiation
Photons with a long absorption length come out.

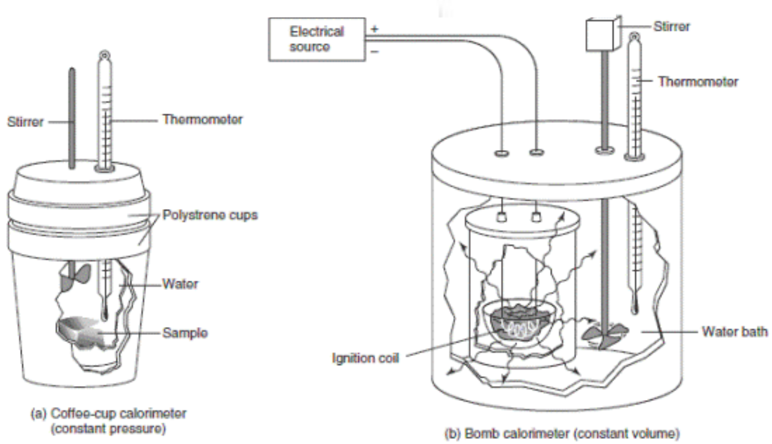


Figure 9.1 Two types of calorimeters.

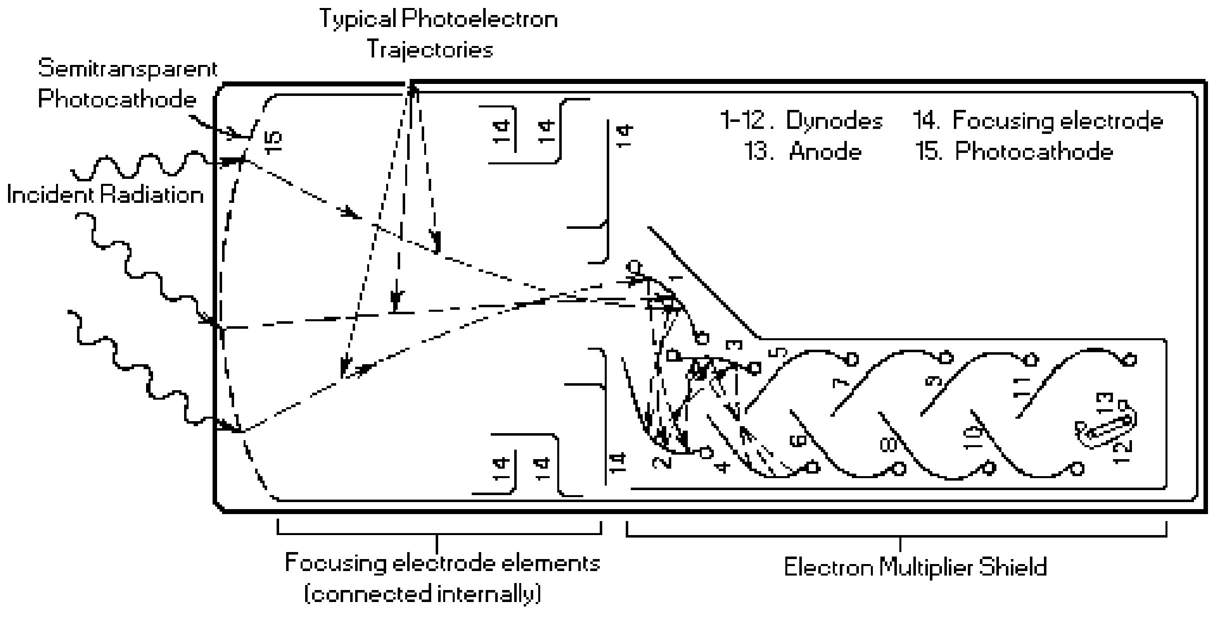
$\propto E\gamma$

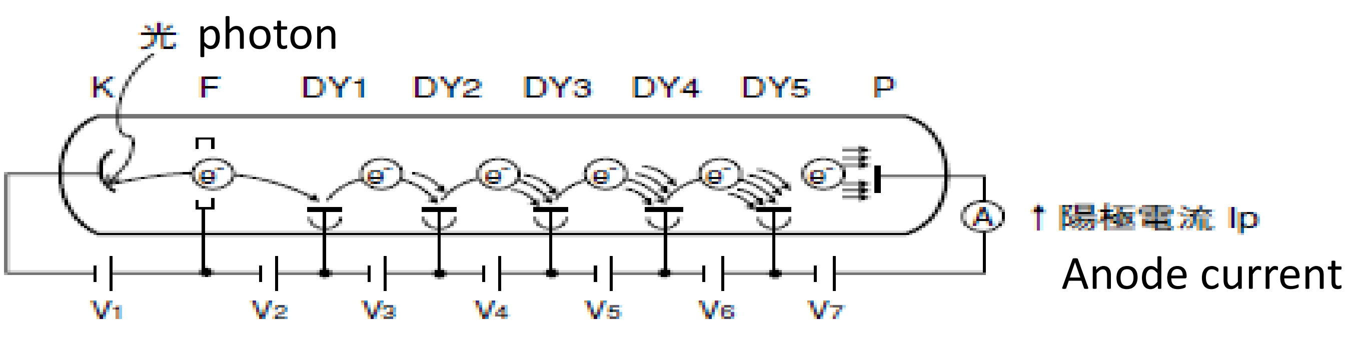
=Electromagnetic Calorimeter

Photomultiplier Tube (PMT)

- One of widely used detector. You might be already familiar with it.

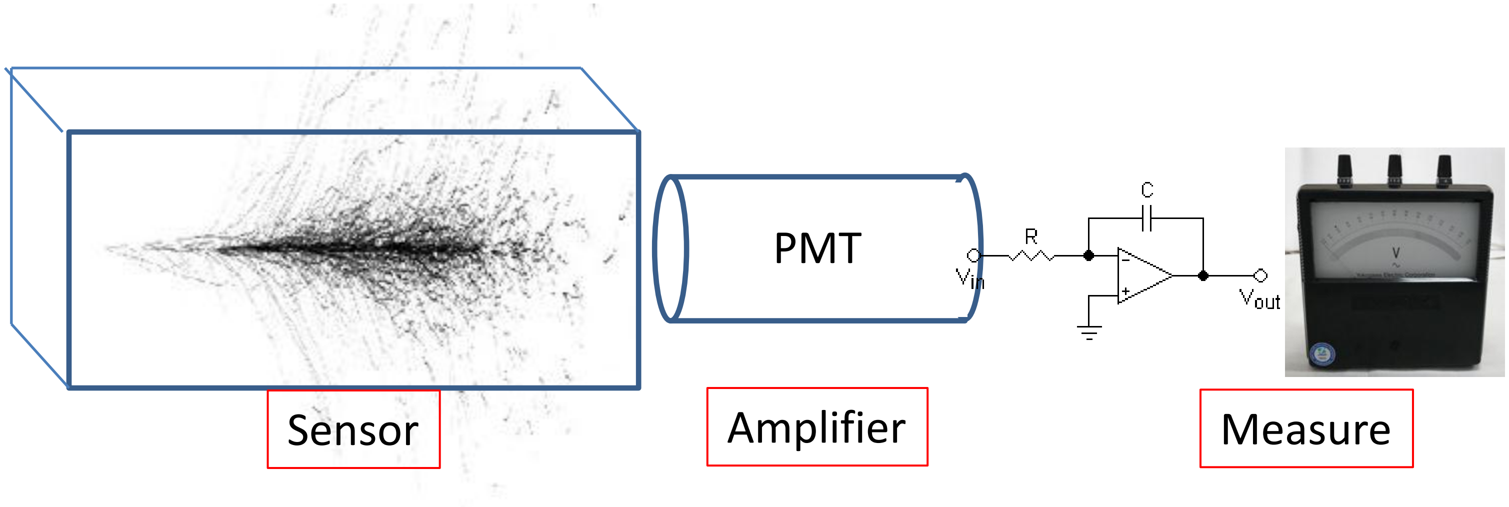
PMT structure

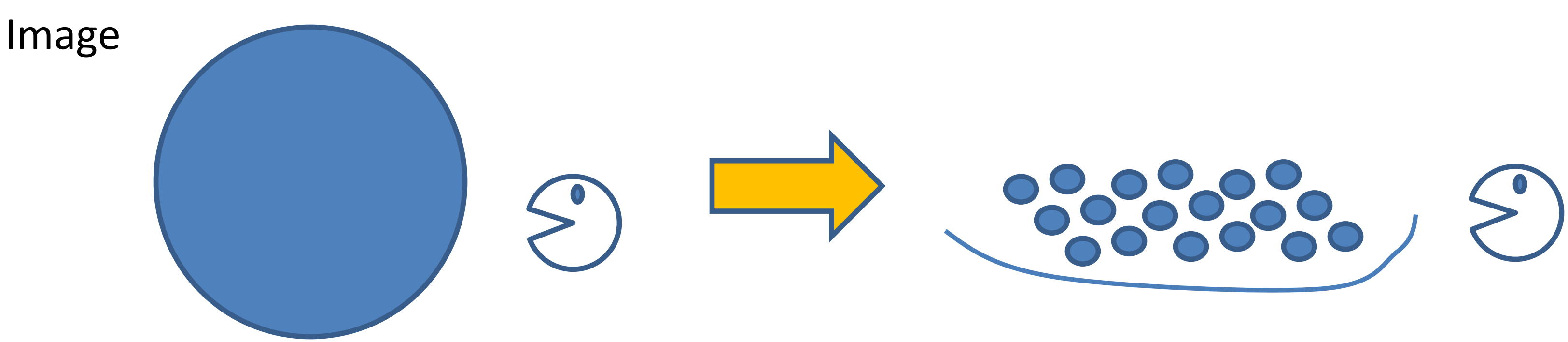




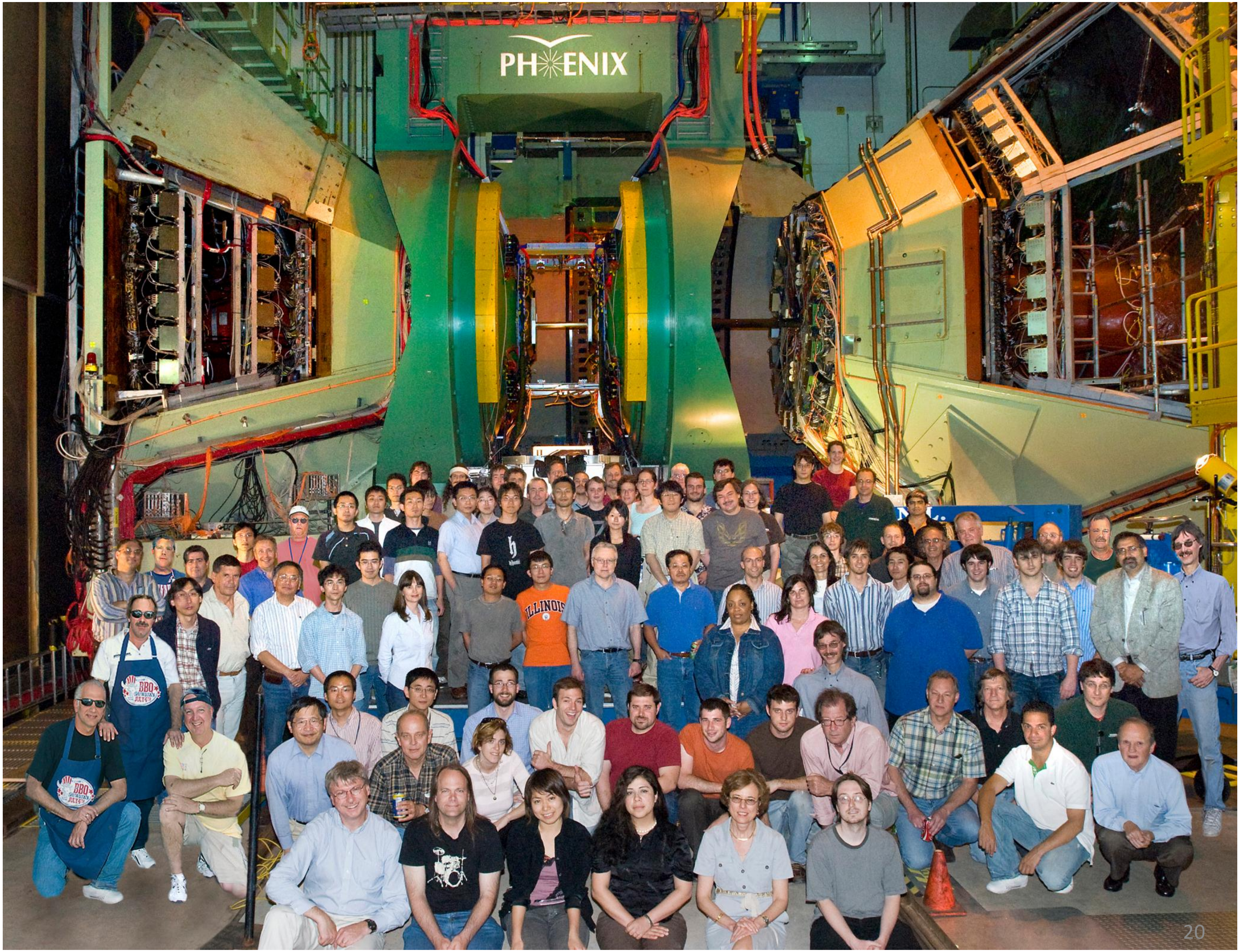
Detection principle summary

- Electromagnetic Calorimeter (EMCal)

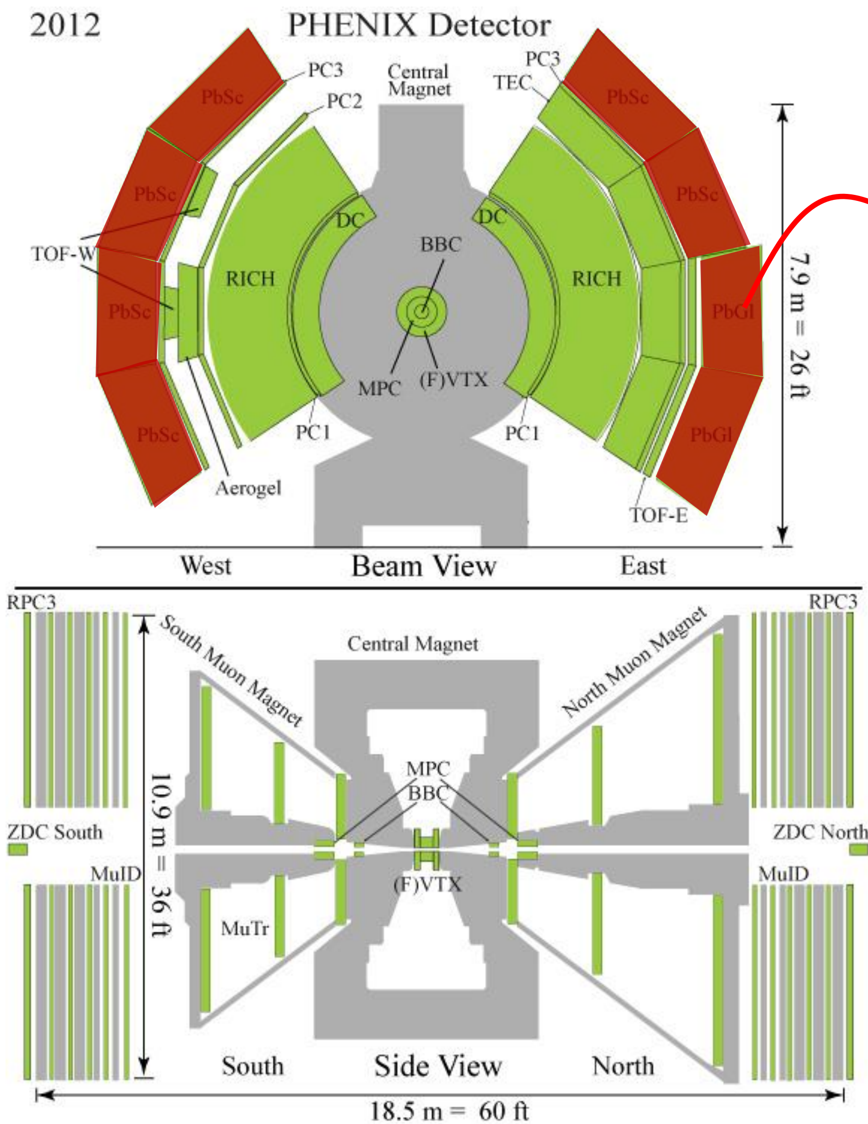


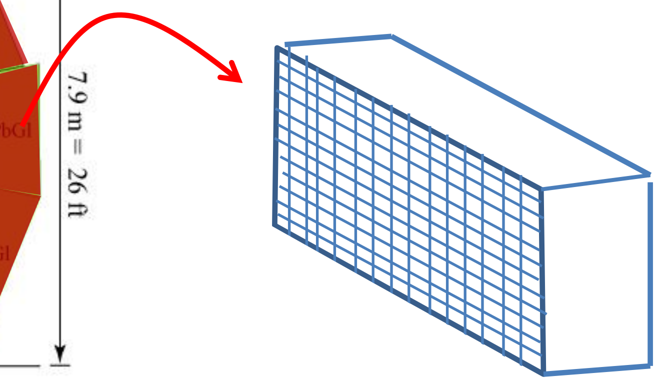


APPLICATION
(PHENIX EXPERIMENT)


PHENIX
ILLINOIS

PHENIX EMCal





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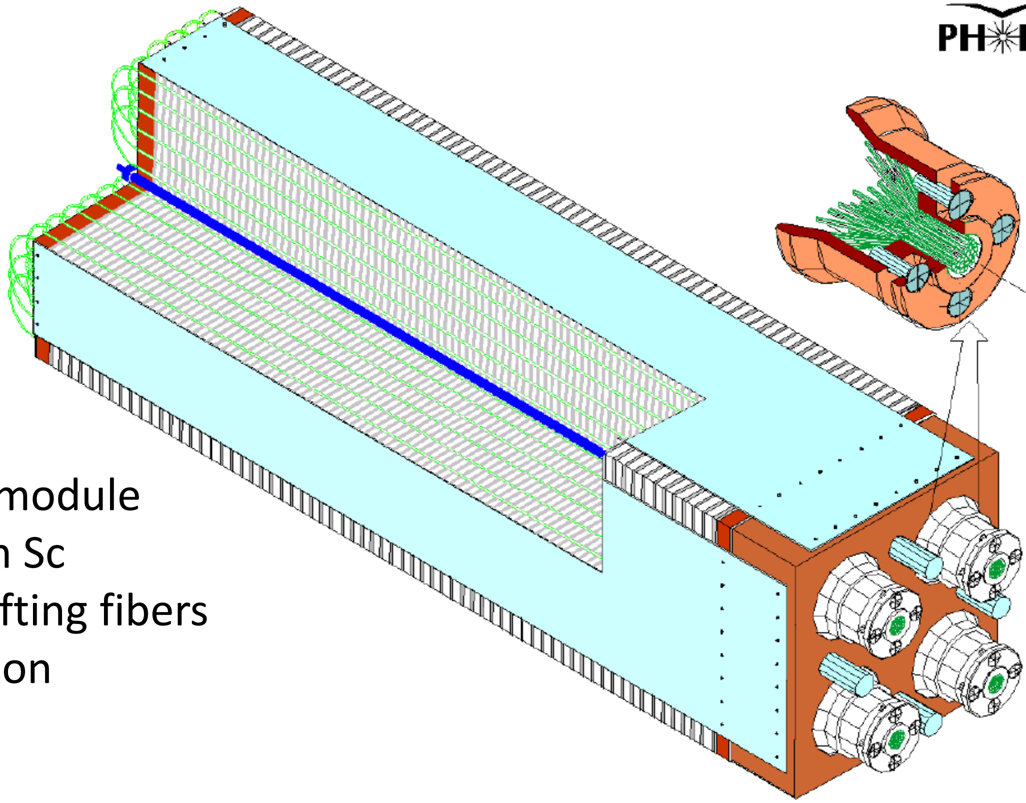
Many sets of

EMCal types

2 sectors : PbGl (crystal)

6 sectors: PbSc (sampling)

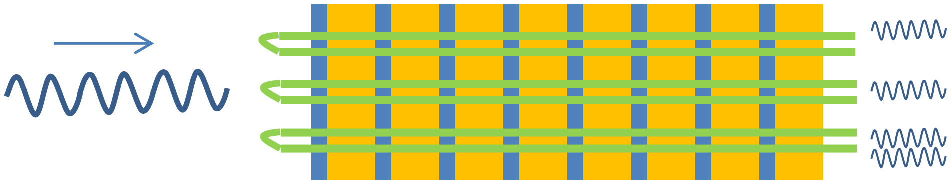


PbSc Quad tower module

1.5mm Pb, 4mm Sc

Wavelength shifting fibers

for light collection



What can we learn from old detectors?

PHENIX design was in 1980-1990's

- Since the basic photon interaction is the same, detectors are not very different.
- The size is different.

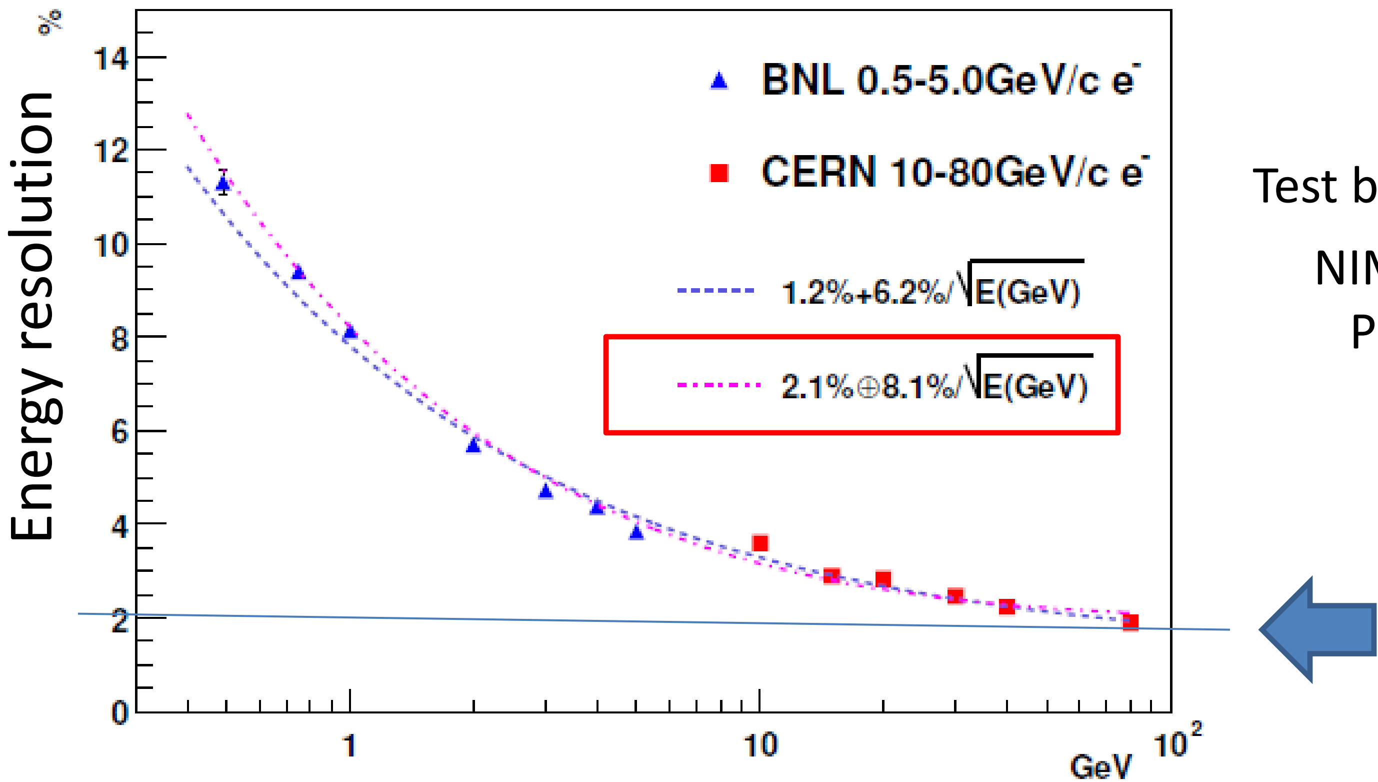
- For the detection principle, old text books are still useful.

Energy resolution (σ_E/E)

- (a) Sampling Fluctuations
- (b) Noise, Pedestal Fluctuations
- (c) Non uniformities, Calibration errors, Incomplete shower containment (leakage)

$$\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c \qquad \sigma_{total} = \sqrt{\sigma_a^2 + \sigma_b^2 + \sigma_c^2}$$

σ_E/E



Test beam result:

NIMA499 521

PHENIX PbSc EMCal

Usually it gives the best performance with a subset of detector.

$$\frac{\sigma}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

The "c" term is often dominant in the real experiment.

Calibration

- Energy scale (Signal $\rightarrow$ Energy)
- Uniformity (25k channels) (It determines the constant term)

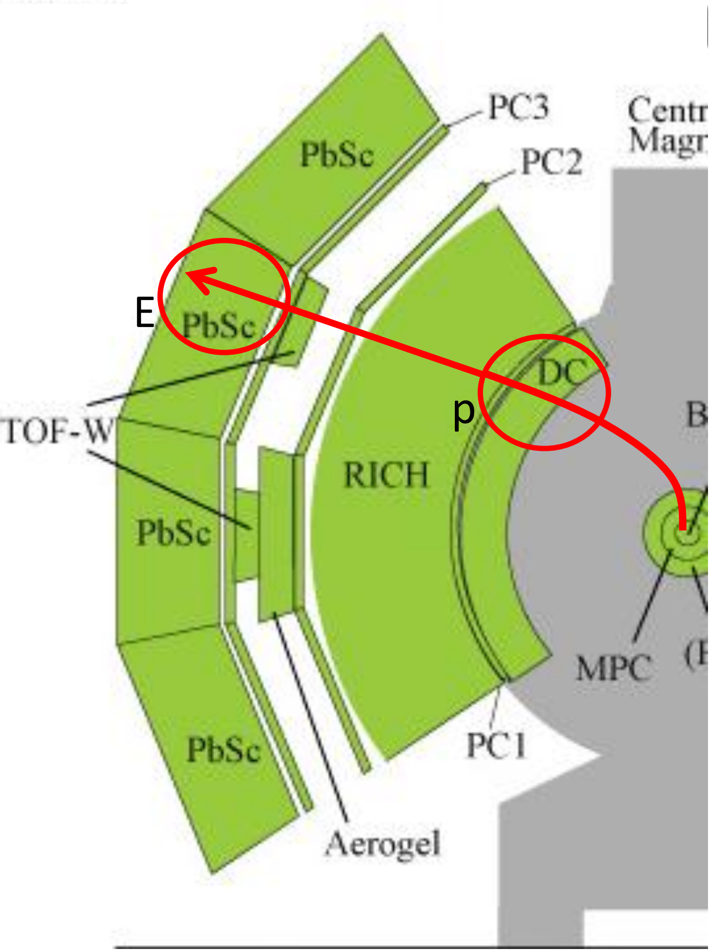
- Methods
  - Based on other measurements
  - Based on physics processes

In the following slides, I will show various methods.
(a few pages/method)

Based on other measurements

- Test beam
- Electron Energy/Momentum ratio
  - The tracking system measures the momentum.
- Laser light input
  - PIN photo diode for the light intensity.

Electron E/p (=Energy/Momentum)



A electron is bent by the magnetic field.
The momentum measured by tracking.

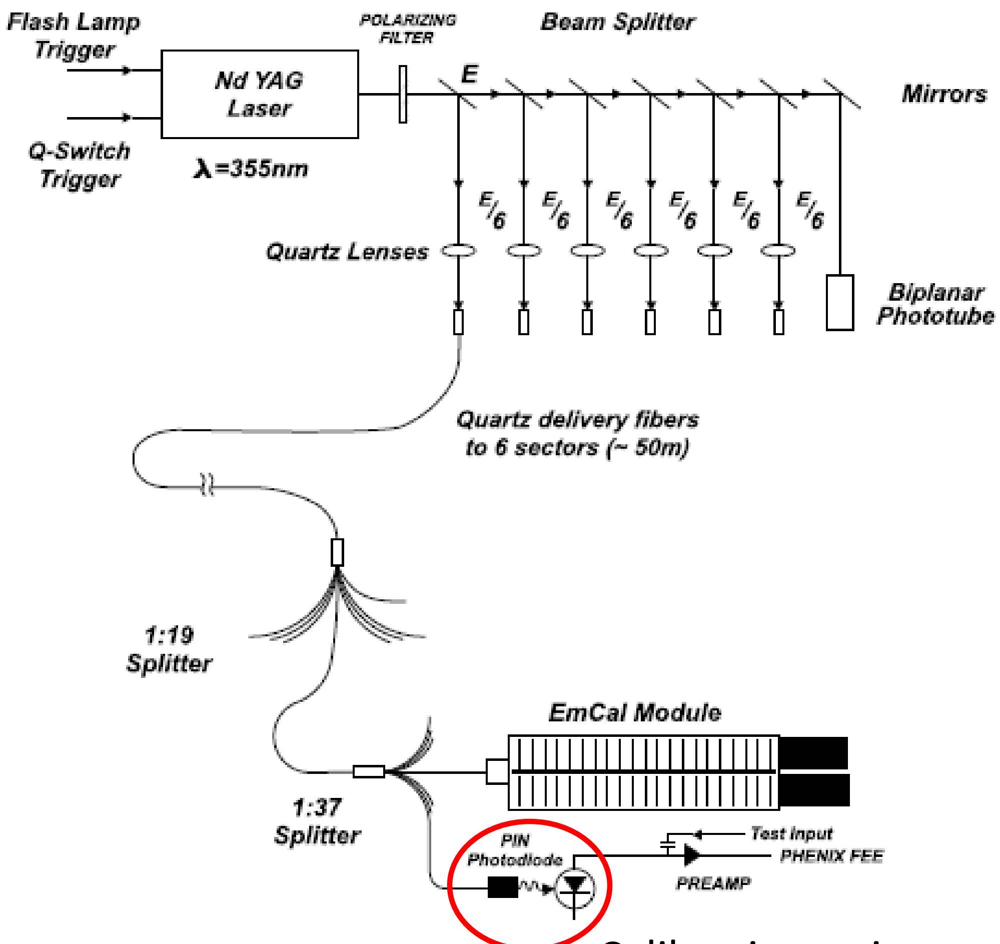
Electron ~ photon response

Compare energy (E) and momentum (p)
(The electron mass is negligible. So E/p=1)

Issue : low statistics

Laser input

For the uniformity



Calibration point

Fig. 2. Laser light distribution and monitoring system

PIN photodiode
didn't work as we expected.

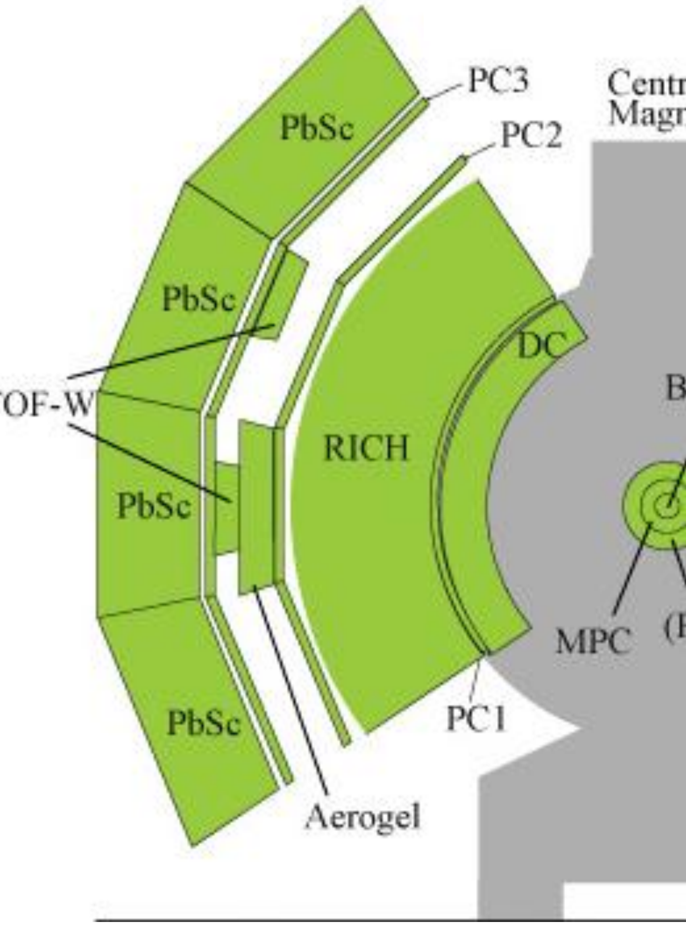
Currently the system is used to check the relative time dependence of each tower.

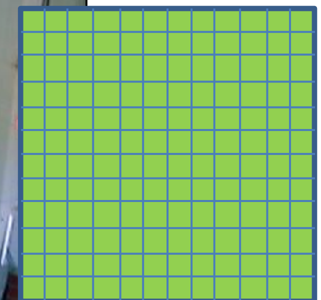
Based on Physics processes

- Spectra shape
- Minimum ionizing particle (MIP)
- π^0 decay, mass

Spectra slope

for uniformity

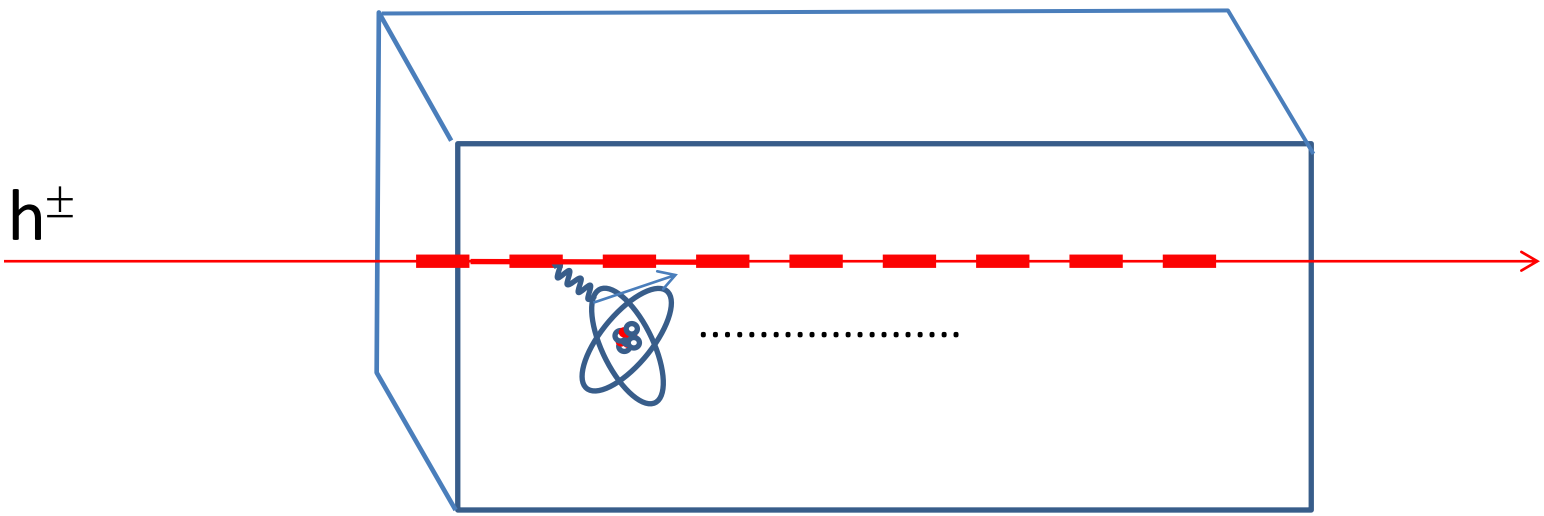




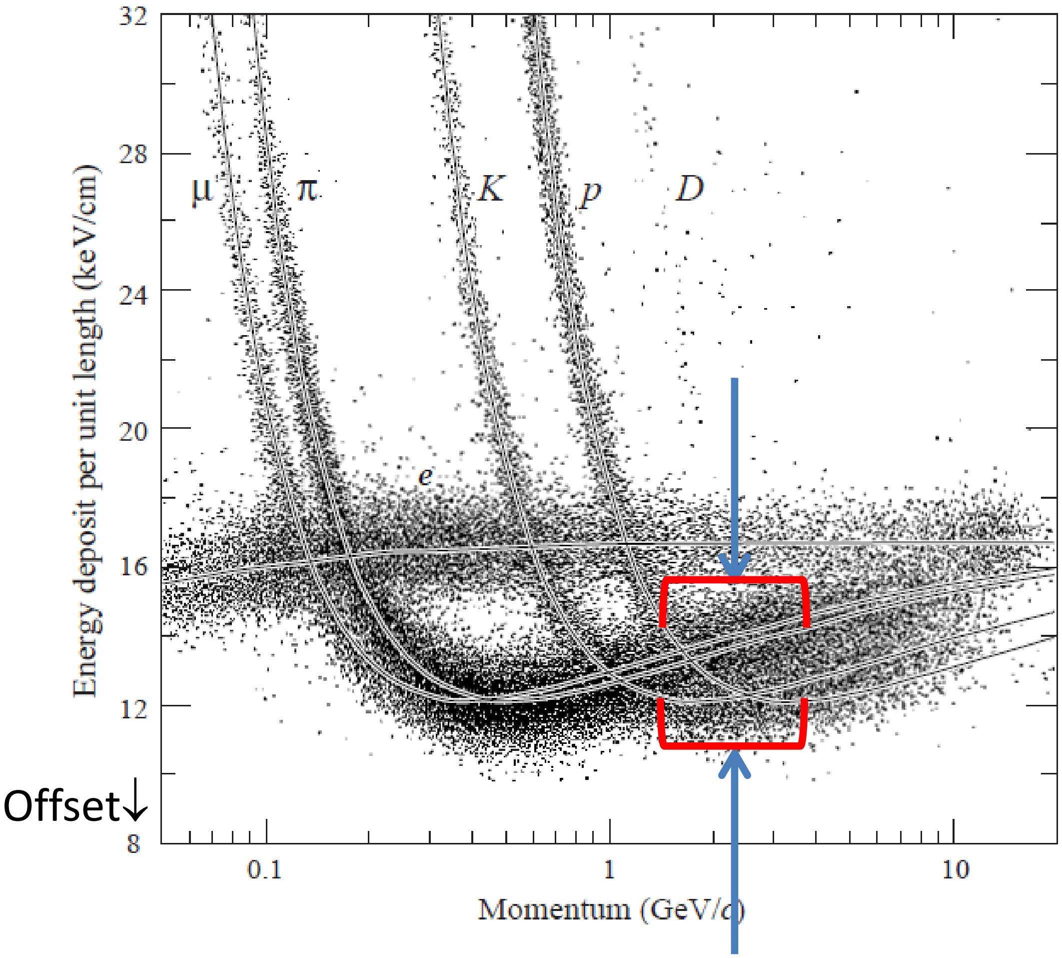
For each tower.

MIP (Minimum ionizing particle)

~60% of charged particles penetrate PHENIX EMCal.
As it gets through the material, it kicks electrons of atoms. (Ionization)



MIP (Minimum ionizing particle)



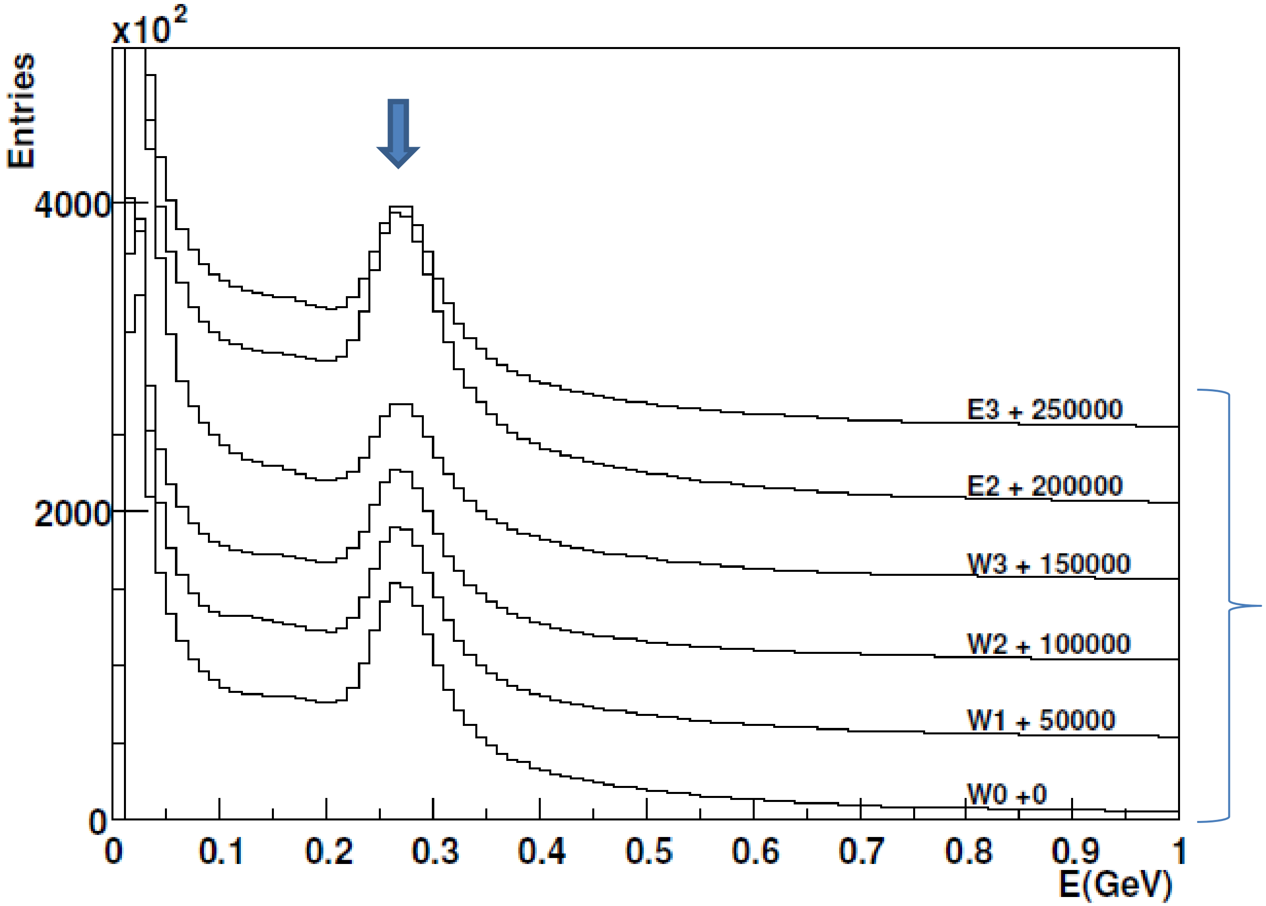
From particle data group
This plot is for 8.5atm Ar-CH4 80:20

The point here is the weak dependence of momentum and particle species.

Typical MIP is 1.5MeV/(g/cm^2)

MIP peak in the EMCal

For scale and uniformity



Different Sectors of EMCal

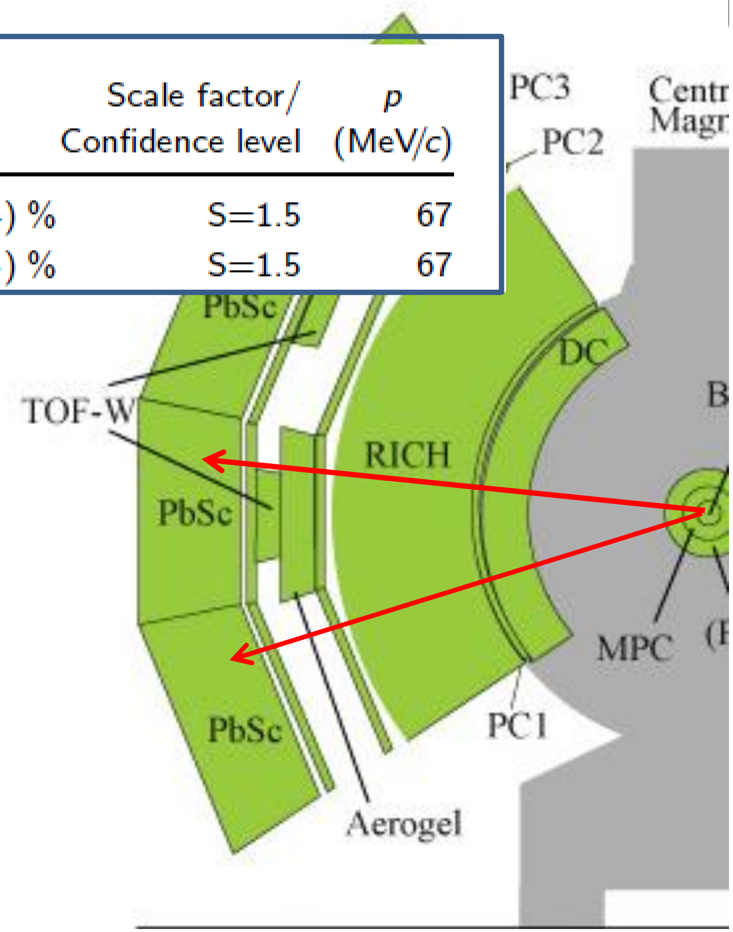
π^0 mass

$\boxed{\pi^0}$

Mass $m = 134.9766 \pm 0.0006$ MeV (S = 1.1)
$m_{\pi^\pm} - m_{\pi^0} = 4.5936 \pm 0.0005$ MeV
Mean life $\tau = (8.4+\text{-}0.4) \times 10^{-17}$ s (S = 2.3)
$c\tau = 25.2$ nm

π^0 DECAY MODES	Fraction (Γ_i/Γ)	Scale factor/ Confidence level	p (MeV/c)
2γ	(98.823 ± 0.034) %	S=1.5	67
$e^+ e^- \gamma$	(1.174 ± 0.035) %	S=1.5	67

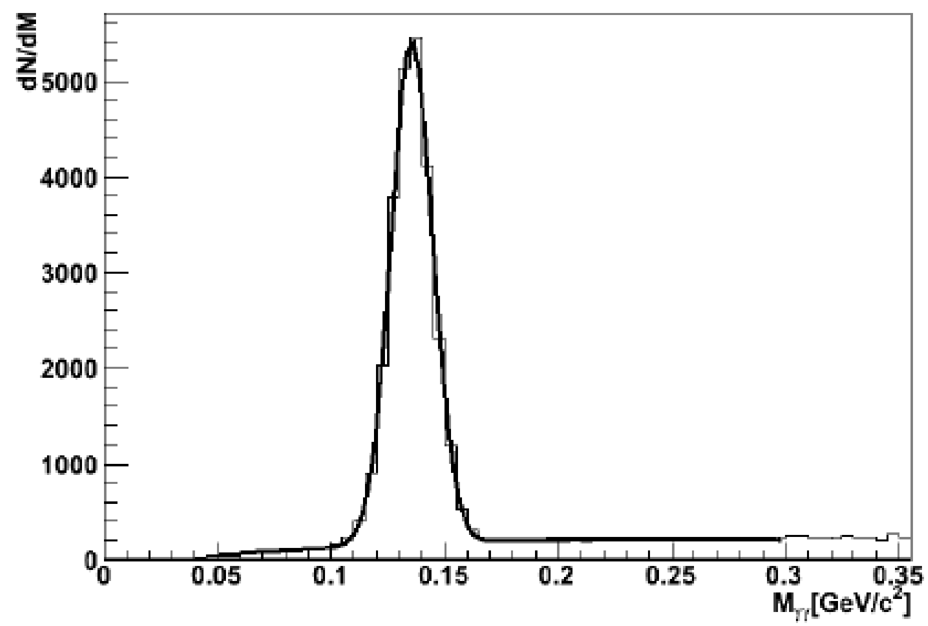
$\pi^0 \rightarrow \gamma\gamma$



π^0 mass in the EMCal

For scale and uniformity

$$M_{\gamma\gamma} = 2\sin\frac{\theta}{2}\sqrt{E_1 E_2}$$



Get the mass peak for every tower.

We applied an iterative process.

Always there are details

- Electron E/p : difference to photon
- Slope : incident angle dependence
- MIP : Only at low E point.
- π^0 mass : shift due to the slope and the finite energy resolution (smearing). The position resolution eventually goes in.

PHENIX calibration summary

Method	for	Type	Comment
Electron E/p	Scale	Other det.	Low Stat
Laser input	Uniformity	Other det.	Limited usage
Spectra slope	Uniformity	Physics	Angle dependence
MIP	Scale, Uniformity	Physics	One low E point
π^0 mass	Scale, Uniformity	Physics	Smearing

It is important to have multiple methods for the cross check.

Summary

- Photon is an important probe.
- It is a particle style of electromagnetic wave.
- Photon and electron are twins.
- Photon and electron produce a shower.
- Electromagnetic calorimeter is used to measure photons in high energy experiment.
- Calibrations are the key for the performance.

What I didn’t cover

- Position resolution
- Timing resolution

- A lot of other techniques